UAMAC: Unidirectional-Link Aware MAC Protocol for Heterogeneous Ad Hoc Networks*

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Abstract. In heterogeneous ad hoc networks, high-power nodes could potentially interfere with any on-going transmissions of low-power nodes. In this paper, we propose a unidirectional-link aware MAC protocol (UAMAC) which prevents such an interference problem by reserving the wireless channel of unidirectional high-power node selectively over one-hop. Our preliminary performance results show that the UAMAC works well in these heterogeneous environments with unidirectional links.

1 Introduction

Recent research in ad hoc networks has focused on medium access control (MAC) and routing problems, resulting in many different protocols proposed [1]. Most of such protocols typically assume that the transmit power capability of nodes in networks is homogeneous. In reality however, it is reasonable to assume that nodes in ad hoc networks have some degree of heterogeneity with various power capabilities and transmission ranges. For instance, there are many handheld devices that have low-power capabilities running with battery. On the other side, there are more powerful devices such as large file servers. Usually these devices are equipped with more powerful network components than handheld devices.

The IEEE 802.11 [2] MAC protocol has been popular for use in mobile ad hoc networks. According to this protocol, a hidden node problem [3] is prevented by exchanging small RTS and CTS control frames. It works pretty well in the homogeneous network. However, its performance may degrade significantly, when used in the heterogeneous network environment [4, 5]. The main reason for this degradation is that in certain scenarios high-power nodes cannot overhear the exchange of the low-power RTS or CTS frames. In such a case, they can simply initiate their own transmissions to another node, causing an increased number of collisions. Furthermore, due to this effect, low-power nodes may suffer from lack of sufficient channel reservation time to communicate with others successfully. Hence, more efficient MAC protocols are needed to handle unidirectional links properly in ad hoc networks.

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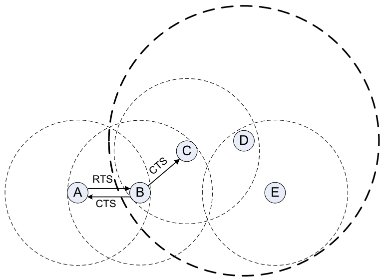


Fig. 1. An example of heterogeneous ad hoc networks, a high-power node D cannot hear RTS/CTS exchange sent by low-power nodes A and B

In this paper, we focus on the efficient MAC protocol design in heterogeneous ad hoc networks. We propose the UAMAC (Unidirectional-link Aware MAC) protocol that detects unidirectional links and prevents any possible interference caused by 'blind' high-power nodes. Our UAMAC can reduce collisions occurred by high-power nodes and improve throughput at the MAC layer.

2 Related Works

Before addressing related works, we will examine the problem of the IEEE 802.11 MAC protocol in the heterogeneous networks more closely. The problem may occur in ongoing transfer of low-power nodes when some blind high-power nodes (that unable to hear the RTS/CTS exchange between the low-power nodes) attempt to transmit to another node. In the Fig.1, RTS/CTS exchange of low-power nodes A and B is not reached to high-power node D, because node D currently exists outside the propagation range of nodes A and B. Let us assume that, while the data exchange between A and B is in progress, the high-power node D tries to initiate its own transmission to another node, for example node E. In this case any receiving packets at node B can be lost due to interference from high-power node D. The simulation results in previous works [4] show that the performance of low-power nodes degrades significantly in the heterogeneous network as compared to that in a homogeneous network.

In [4], the authors have attempted to solve this problem by enlarging CTS propagation range over one-hop. Thus, any nodes that hear CTS frames are required to broadcast further once or twice more in forms of Bandwidth Reservation (BW_RES) control frames. The objective of this broadcast is to let any high-power nodes in the neighborhood know about ongoing RTS/CTS exchange between the sender and the receiver so that they would in turn inhibit their own transmissions for the duration in the BW_RES frame. Although a fairness of low-power nodes can be improved, throughput at the MAC layer will be more degraded since the increased overhead incurred in propagating the BW_RES frames.

[5] proposed another scheme to solve this problem of performance degradation in [4]. The authors point out that the reason of this degradation is due to a collision of multiple BW_RES frames. More than two nodes simultaneously forwarding BW_RES may cause a collision. To prevent this situation, when any node needs to forward BW_RES frame (note that it is renamed as FCTS(Forward-CTS) in [5]), it first senses the wireless channel. Only if the channel is not busy, the node is allowed to transmit the FCTS. In order to further reduce excessive BW_RES frame overhead, only high-power nodes forward the BW_RES frames. In addition, [5] also proposed that high-power nodes receiving RTS framed transmit a Forward-RTS (FRTS) frame. It is to prevent any high-power node interfering other nodes that are supposed to receive ACK packets. In this approach however, the amount of increasing control frames holds practically.

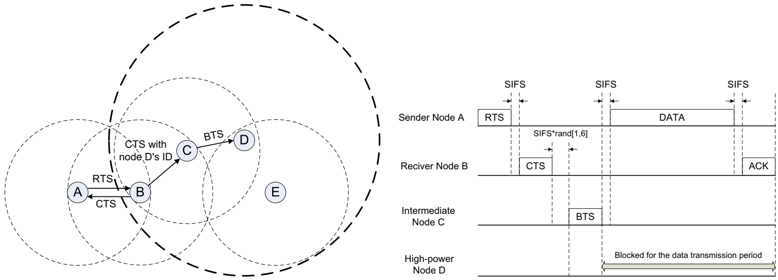
All of these previous works use a flood-based broadcast algorithm for enlarging propagation range of RTS/CTS frames. However these approaches could increase control message overheads. We propose more efficient protocol that detects unidirectional link nodes and selectively broadcasts additional control messages to unidirectional high-power nodes. Eventually our scheme prevents interference of high-power node with the minimized control message overhead.

3 UAMAC (Unidirectional-Link Aware Mac)

In UAMAC (Unidirectional-link Aware MAC), a node detects the presence of unidirectional links to its neighbors by utilizing some distance estimation scheme. The UAMAC assumes that there are specific frames carrying additional information to estimate a link status between a transmitter and a receiver. This information would be carried in periodic beacon frames or in RTS/CTS frames only exchanged when there are data packets to transmit. Due to the excessive overhead of periodic beacon exchange, we choose the later approach in our simulation.

The basic idea behind the UAMAC is represented by example. In Fig. 2(a), when low-power node A exchanges RTS/CTS frames with another low-power node B, node A compares its maximum transmission range to an estimated distance between transmitter (node A) and receiver (node B). If the value of estimated distance from node A to B is larger than the transmission range of node A, node A considers its wireless link to B as a unidirectional link and marks it in the neighbor node list. Otherwise, a link towards B, node A marks as bidirectional in its neighbor node list. Every nodes receive RTS/CTS frames, they update a link status for their neighbors.

Using these neighbor lists, nodes can perform following operations. In Fig. 2(a), node B receives RTS frame from node A and sends CTS frame with its unidirectional link node D's ID, for example MAC address. When node C receives CTS frame, it checks the neighbor node list to see if node D is in the list (i.e. determines whether D is its neighbor or not.) If node D is found, then node C will forward an additional control frame called BTS (Block-To-Send) to D. Consequently, node D will block itself for this time equal to duration in BTS



(a) (b)

Fig. 2. BTS frame propagation and the extended reservation scheme

frame. Therefore, nodes A and B can communicate without any interference from high-power node D.

We have extended the RTS/CTS reservation scheme for adding BTS frame. Each node hearing the CTS frame determines whether it sends a BTS or not. If a node decides to send the BTS frame, it waits until random value (between 1 and 6) of the SIFS units before transmitting the BTS frame. This minimizes collisions caused by multiple simultaneous BTS transmissions from neighbors that hear same CTS frame. In addition, if the transmitter of the CTS frame has no bidirectional link, it sends the CTS frame with unidirectional link node field as blank. When sender node A receives this frame, it transmits data frame immediately without waiting for BTS scheduling period. It helps to minimize unnecessary waiting time in the extended reservation scheme. The whole timing diagram of this extended reservation scheme is shown in Fig. 2(b).

4 Unidirectionality Detection

The question is how to calculate an estimated distance between two communicating nodes, so that it can be compared with the radio transmission range to determine whether the links between two nodes are bidirectional or unidirectional. This can be done as described below.

We can utilize a wireless channel propagation model, i.e., the two-ray ground path loss model that is designed to predict the mean signal strength for arbitrary transmitter-receiver separation distance. In wireless networks, if we know the transmitted signal power (P_t) at the transmitter and a separation distance (d) of the receiver, the receiver power (P_r) of each frame is given by the following equation:

$$P_r = \frac{P_t \times G_t \times G_r \times (h_t^2 \times h_r^2)}{d^4 \times L} \qquad (1)$$

G_t and G_r are transmitter and receiver antenna gain, and h_t and h_r are transmitter and receiver antenna height. The above Eq.(1) states that the distance between two communicating nodes can be estimated at a receiver side, if the transmitted power level P_t of the transmitter and the power received at the receiver P_r are known. To implement this method, the transmitter should make the transmitted power information available to the receiver, by putting the power information either on a specified message, for example RTS/CTS frames.

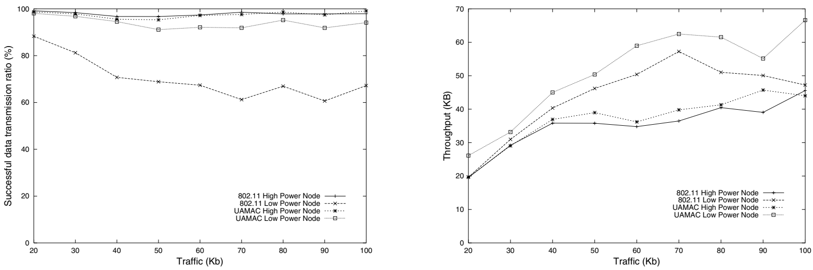
With this estimated distance, we detect unidirectionality between two neighbor nodes. If the estimated distance is shorter than receiver node's communication range with its maximun power, two nodes can communicate each other with bi-directional link. If not, however, a unidirectional link is made between two communication nodes. We can achieve more realistic direcionality assumption by comparing received power level, which is calculated by same channel propagation equation, with a receving threshold.

5 Performance Evaluation

In this section, we evaluate the performance of UAMAC scheme. We performed simulations using ns-2 for a two-level heterogeneous network at nodes' transmission range of $250m$ and $125m$. We use grid topology with total 49 nodes – 4 high-power nodes and 45 low-power nodes. Distance of each node is uniform $100m$ and the whole network size is 700×700 unit square grid. In our simulations, high-power nodes are intentionally located at the four corners separately, because we want they have independent radio propagation area. Traffic pattern we used consists of 8 CBR connections running on UDP, half from high-power nodes and half from low-power nodes. We use static and relatively simple topology as our preliminary performance evaluation. This is because in random topology and mobility, the situations that we want to show in the simulation are easily collapsed by topology change.

We evaluate our schemes in terms of successful data transmission rate and throughput. We define the successful data transmission ratio as percentage of successful data frame transmission after a successful RTS/CTS handshaking. Fig. 3(a) shows the performance of successful data transmission rate with varying data traffic. In the IEEE 802.11 MAC, low-power nodes degrade its successful data transmission rate up to 40% versus high-power nodes. But UAMAC reduces this degradation within 5%. This improvement is achieved through reducing data frame collision caused by interference of high-power nodes.

And then we examine the throughput. We define throughput as total size of received data frame. In Fig. 3(b), it is found that throughput performance of UAMAC is higher than the IEEE 802.11 MAC as much as maximum 19%. This is because UAMAC reduces unnecessary data frame retransmissions through the reducing collisions (as we can see above analysis).



(a) (b)

Fig. 3. Successful data transmission ratio and Throughput

6 Conclusions

In this paper we consider the performance degradation of the IEEE 802.11 MAC protocol in the heterogeneous ad hoc networks. To overcome this problem, we propose Unidirectional-link Aware MAC (UAMAC) scheme. It detects the unidirectional link by the distance estimations, and having this information, it prevents interference of high-power nodes during communication period of low-power nodes. We show that the use of UAMAC can improve throughput up to 19% and alleviate the unfairness cause by the legacy IEEE 802.11 MAC protocol. Future work would include simulation results with mobility scenarios and more realistic environment.

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